

Towards understanding dynamo action in M dwarfs

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ABSTRACT

Recent progress in observational studies of magnetic activity in M dwarfs urgently requires support from ideas of stellar dynamo theory. We propose a strategy to connect observational and theoretical studies. In particular, we suggest four magnetic configurations that appear relevant to dwarfs from the viewpoint of the most conservative version of dynamo theory, and discuss observational tests to identify the configurations observationally. As expected, any such identification contains substantial uncertainties. However the situation in general looks less pessimistic than might be expected. Several identifications between the phenomenology of individual stars and dynamo models are suggested. Remarkably, all models discussed predict substantial surface magnetic activity at rather high stellar latitudes. This prediction looks unexpected from the viewpoint of our experience observing the Sun (which of course differs in some fundamental ways from these late-type dwarfs). We stress that a fuller understanding of the topic requires a long-term (at least 15 years) monitoring of M dwarfs by Zeeman-Doppler imaging.

Key words: stars: low mass – stars: magnetic field – stars: imaging – dynamo

1 INTRODUCTION

The intensive investigation of stellar magnetic activity has already a history of about 40 years, and many important results have been obtained (Hartmann & Noyes 1987; Berdyugina 2009; Saar 2011; Donati 2011; Vidotto et al. 2014; Kővári & Oláh 2014). On one hand, this activity is believed to be similar to some extent to the solar cyclic activity. In particular, the magnetic fields of many types of stars are believed to be excited by stellar dynamo action, driven by the joint action of differential rotation and an additional mirror-asymmetric driver which produces poloidal magnetic field from toroidal. The physical nature of this mechanism is still debated for the Sun, and there are even more uncertainties for other stars. However we have no intention to enter this discussion now and for the sake of simplicity refer to this factor as the α -effect, whatever its physical nature.

On the other hand, magnetic activity in any particular star can look quite distinctively different from the solar case: starspots on the most investigated magnetically active stars are much larger than on the Sun, covering a larger part of the surface than sunspots, etc. These specific features should somehow be related to the properties of stellar dynamos. However in practice any such relation is ill-understood.

In particular, the relation between the magnetic phenomenology of M dwarfs and the underlying stellar dynamo action is a topic of continuing discussions at scientific meetings. Experts in obser-

vational investigations of starspots on M dwarfs have stressed many times that some input from dynamo theory to the problem is very desirable. There is a general feeling that there is a basic difference between dynamo action in M dwarfs which are fully convective stars, and in the Sun which has a relatively thin convective shell. As far as we can recall, it was E. Ergma who attracted the attention of one of us (Dmitry Sokoloff) to the problem as early as 1993.

There are many theoretical models that explore various details of stellar dynamo action for a range of stellar types, including M dwarfs (e.g., Chabrier & Küker 2006; Browning 2008). 3D dynamo models give very important information concerning magnetic activity of fully convective stars. In particular, the models clarify spot formation mechanism (Yadav et al. 2015) and predict the location of dipole-dominated M-dwarfs (Schrinner et al. 2012; Gastine et al. 2012, 2013; Schrinner et al. 2014) in terms of their rotation velocities and convection efficiency, giving in this way an observational test for verification of the model. However, sometimes the predicted magnetic configurations depend significantly on various small and quite uncertain factors, such as the boundary conditions at the stellar surface; it is thus very difficult to adequately reproduce all these details in a particular dynamo model.

Therefore, although considerable progress has been made in developing comprehensive 3D MHD simulations of fully or nearly fully convective stars (e.g. Dobler et al. 2006; Browning 2008; Schrinner et al. 2012; Gastine et al. 2012; Schrinner et al. 2014; Yadav et al. 2015), these models are not yet fully satisfactory. For

instance, applied to the Sun the 3D models still have difficulties in tuning parameters to reproduce the observed butterfly diagram.

Depending on assumptions and approximations used in numerical simulations, modern dynamo models may predict different dynamo states. For instance, for fully convective stars it is often suggested that dynamos will be of α^2 type, and often non-axisymmetry is predicted. However, the steady α^2 solutions seem to be not fully in accordance with observations, where axisymmetric and non-axisymmetric configurations are found in very similar objects (see Sect. 4, also Gastine et al. 2014). Note that relatively weak toroidal field is often taken as an indicator of non-axisymmetry. On the other hand, as was shown in e.g., Schrunner et al. (2012), oscillating α^2 -dynamos are also possible under certain conditions.

Furthermore, very recent dynamo models predict that dynamo can be bistable, the eventual stable state depending on initial conditions. This could explain the observed distributions of the magnetic field geometries among objects with similar parameters (see e.g., Schrunner et al. 2014).

One of the difficulty in using 3D models for the extensive exploration of stellar dynamos is the requirement of large computational resources, making it difficult to use outside of a substantial programme, and limiting possible exploration of parameter space. As alternative, the “hybrid” models that use transport coefficients deduced from MHD simulations in mean field models may provide a more satisfactory way forward (e.g., Dubé & Charbonneau 2013; Pipin & Kosovichev 2013). Nevertheless, in spite of a wide variety of available models, none of them provides a complete understanding of dynamo action in low mass stars.

The above considerations suggest that progress in theoretical modelling and observations has led to a rather strange situation where quite amazing advances in the last 40 years have brought rather less physical understanding of the problem than might have been anticipated. Our feeling is that coordination of efforts between observers and dynamo modellers is urgently needed to further progress in the topic.

We envisage the format of the coordination to be as follows. A risk has to be taken and a particular approach to dynamo modelling has to be accepted as a starting point. A list of magnetic configurations that can be expected for M dwarfs in the framework of this basic model has to be constructed, together with observational tests capable of distinguishing the configurations observationally. If possible, the existing observational data have to be used to identify the configurations, and the perspective of future observations should be discussed. The point is that the full inspection of the list may (and will) be quite demanding on telescope time and other material resources, and the community will have to make a reasonable decision on how to manage resources in order to achieve this goal. Further steps in development of the model would have to be motivated by particular difficulties in interpretation of observations.

The aim of this work is to explore the magnetic configurations that can be excited by a more or less standard mean-field dynamo model based on differential rotation (Ω -effect) and mirror-asymmetric convective motions (the α -effect), and then to follow the above plan as far as it is possible at the moment. We appreciate that several important points of our (as any other) dynamo model are debatable and can only, at best, partially represent the true physics. In particular, we recognize that in other models the differential rotation may be substantially reduced compared to the model we consider in this work. We stress however, that this paper is more a demonstration of principle than an attempt to offer a definitive resolution of any particular issue, and should be

viewed as such. We do not attempt to give a complete review of the field, but rather just to indicate some key points and references. Of course, the parameters and details of the models are likely to be modified in course of progress in understanding of the topic.

This paper is in some sense related to the recent paper by Kitchatinov et al. (2014) who, however, approached the topic from a quite different viewpoint. They suggested an explanation for the observed phenomenology of magnetic activity of M dwarfs in a way analogous to the solar case: that explanation does not require the idea of dynamo bistability. Here, however, we do not exclude the latter in principle and address the problem from an alternative viewpoint, and discuss the richness of dynamo models for M dwarfs that have more or less comparable complexity. As we will show below, four rather than two configurations look possible and we suggest how to clarify which (if any) are really of potential interest, and whether something more complex is needed.

2 THE DYNAMO MODEL

Dynamo theory explains stellar magnetic activity by two basic effects: i) poloidal field production from toroidal field by cyclonic motions (the α -effect) and ii) conversion of poloidal field back to toroidal by the action of differential rotation (the Ω -effect) and possibly by the α -effect as well. The efficiency of the two effects in generating magnetic fields are measured by the dimensionless parameters

$$C_{\Omega} = \frac{\Delta\Omega R_{\text{star}}^2}{\eta_T} \quad (1)$$

for the Ω -effect ($\Delta\Omega$ is a measure of the angular velocity variation within the convection zone and η_T is the eddy magnetic diffusivity), and

$$C_{\alpha} = \frac{\alpha_0 R_{\text{star}}}{\eta_T}, \quad (2)$$

for the α -effect (Krause & Rädler 1980), where α_0 is a representative value.

For our illustrative purposes we use the same dynamo model as Kitchatinov et al. (2014) and therefore describe it only briefly. The model is of $\alpha^2\Omega$ -type, i.e. taking the toroidal field generation by the α -effect into account. The differential rotation in M dwarfs is small (Barnes et al. 2005) and it is often neglected in models of their dynamos, thus giving α^2 -dynamos. We note that it is possible to obtain similar magnetic field configurations with or without differential rotation. For instance, axisymmetric fields have been obtained in recent simulations with pure α^2 -dynamos (e.g., Schrunner et al. 2012). On the other hand, mean-field models of α^2 -dynamos by Chabrier & Küker (2006) (which allow for the rotationally induced anisotropy of the α -effect) predict non-axisymmetric global fields similar to an equatorial dipole. But if differential rotation is present, it may oppose the non-axisymmetry by converting azimuthal variations into small-scale radial or meridional structure, enhancing diffusive decay (Moss & Brandenburg 1995). Because the results of simulations are very sensitive to approximations and assumptions made, in the mean-field models that we use in this paper we explicitly include the contribution from differential rotation. The point here is that although $\Delta\Omega$ decreases with decreasing stellar mass, the eddy magnetic diffusion η_T decreases even faster so that the parameter C_{Ω} (Eq. 1) *increases*. This trend was found in mean-field models of differential rotation by Kitchatinov & Oelskoy (2011). Note again that this model does not prescribe the eddy transport coefficients but estimates them in

terms of the entropy gradient, the entropy being a dependent variable of the model. In particular, the value $v_T \approx 1.2 \times 10^{11} \text{ cm}^2 \text{ s}^{-1}$ was estimated for the middle radius $r = R_{\text{star}}/2$ of a $0.3M_{\odot}$ star rotating with a period of 10 days (v_T varies moderately with depth). We shall use the differential rotation computed for this fully convective star in our dynamo model. The eddy magnetic diffusion is of the same order of magnitude as the eddy viscosity (Yousef et al. 2003), so that the magnetic Prandtl number,

$$P_m = v_T / \eta_T, \quad (3)$$

does not differ much from unity. Taking $P_m = 1$ gives $C_{\Omega} \approx 290$ which is not small in spite of a rather small differential rotation of about 1.5% (see Fig. 1 in Kitchatinov et al. 2014).

The value of C_{α} (Eqn. 2) is more difficult to estimate. The origin of the α -effect is not certain for the Sun (Charbonneau 2014) and even less so for M-dwarfs. Order of magnitude estimation is nevertheless possible. The Rossby number $Ro = P_{\text{rot}}/\tau$ is small for the $0.3M_{\odot}$ star considered with $P_{\text{rot}} = 10$ days (τ is the convective turnover time with a characteristic value of a few months (e.g., Barnes & Kim 2010)). The α_0 parameter for this case of convection strongly affected by rotation is expected to be close to its maximum possible value of the convective velocity $u_c \sim 3\eta/\ell$; ℓ being the mixing length. The estimate $C_{\alpha} \sim 3R_{\text{star}}/\ell$ follows from Eq. (2). With the plausible value of $R_{\text{star}}/\ell \sim 10$, this gives $C_{\alpha} \sim 30$, which is not much above the critical C_{α} values for onset of dynamo action in our model (a stellar structure model gives $R_{\text{star}}/\ell = 4.3$ for the middle radius $r = R_{\text{star}}/2$ leading to a somewhat smaller C_{α}).

It may be expected, however, that back reaction of generated magnetic fields on motion affects primarily the α -effect (Brandenburg & Subramanian 2005). The majority of mean-field dynamo models employ the α -quenching as the only nonlinearity. The quenching reduces C_{α} to close to the threshold value for onset of dynamo action.

Note that estimates of C_{α} and C_{Ω} suggest the importance of differential rotation only in the models that we have chosen to use in this paper. This, of course, does not exclude the pure α^2 -dynamo action in M dwarfs, as was stressed above. However, the theoretical ability to predict dynamo governing parameters does not allow one to obtain firm predictions and we believe that observations may play a decisive role here.

We apply our kinematic dynamo model to estimate the threshold values of C_{α} for magnetic fields of different equatorial and axial symmetries. Our model assumes uniform diffusion and that the α -effect is uniform with radius and varies as $\cos \theta$ with co-latitude θ , $\alpha = \alpha_0 \cos \theta$. The model solves the eigenvalue problem for the mean-field dynamo equations (cf., e.g., Krause & Rädler 1980) numerically by applying a grid point method in radius and a latitudinal expansion in Legendre polynomials. Computations were performed on a uniform radial grid of 301 points, and with 40 Legendre polynomials in the latitudinal expansion. Vacuum conditions were applied at the outer boundary. These conditions demand that the toroidal field vanishes at the surface. We cannot exclude however the possibility that the vacuum boundary condition is not the whole story. It is possible to have a field above the surface which is force-free, with finite toroidal field, e.g. Mestel (1966), later Milsom & Wright (1976), see also the discussion in Moss & Sokoloff (2009).

Our model takes α to be independent of radius. Arguing from a possible correlation with the kinetic helicity (which is often used as a proxy for the α -effect), it might be appropriate to take α as an increasing function of radius. As stressed above, we only wanted to provided an illustrative model on which to hang our arguments,

rather than to provide an extensive exploration of parameters, and so did not pursue this.

For numerical reasons the model requires an inner radial boundary. This artificial boundary was imposed at $r_1 = 0.1R_{\text{star}}$ ($R_{\text{star}} = 212 \text{ Mm}$). Conditions for an interface with a perfect conductor were imposed at the inner boundary.

Our toy model has a distinctly non-cylindrical rotation profile (Fig. 1 of Kitchatinov et al. 2014), in contrast to predictions of 3D simulations of rapidly rotating models with strong dynamo action (e.g. Browning 2008). Feedback from Lorentz torques can reduce differential rotation. Weaker fields will merely modify the underlying rotation field (e.g. Moss & Brooke 2000).

We appreciate that a number of potentially significant changes connected with the inclusion of non-linear effects (α -quenching, Lorentz force, etc.) could be made to the model and this could affect the saturated states (e.g., Moss & Brooke 2000; Browning 2008). To avoid these complications, below we consider only linear models. As was stressed above, we prefer to start our exploratory work with simple models that will be advanced once required by the analysis of observed data.

3 DYNAMO EXCITED MAGNETIC FIELD CONFIGURATIONS

We use the standard notations Sm and Am for global modes of magnetic fields (cf. Krause & Rädler 1980), where the first letter S or A denotes field configurations that are symmetric or antisymmetric, respectively, with respect to the equator. In this notation, m is the azimuthal wave number. A0 and S0, therefore denote axisymmetric global fields, which can be steady or oscillatory. A1 and S1 are non-axisymmetric modes with $m = 1$; each field component changes sign twice over an entire longitudinal circle. The modes with $m \geq 2$ normally have dynamo excitation thresholds that are too high for us to consider them as a probable outcome of global dynamo action in M dwarfs. All the global modes combine poloidal and toroidal field components. The meaning of toroidal and poloidal fields for axisymmetric modes is well known. Lines of toroidal fields in non-axisymmetric modes lay on concentric spherical surfaces. Poloidal non-axisymmetric fields have toroidal vector potentials and are supported by toroidal currents (see Chandrasekhar 1960, for more details).

Thinking straightforwardly, we have to conclude that the modes that can be excited for the lowest C_{α} , i.e. the A1 mode for $P_m < 1.1$ and S0 for $P_m > 1.1$, are the modes likely to be excited by dynamo action in M-dwarfs. The point however is that the difference in excitation condition between the modes S1 and A1 for lower P_m and between the modes A0 and S0 for larger P_m respectively is quite small and it would be unrealistic to think that contemporary dynamo models are sufficiently near physical reality to support such distinctions. Thus we allow that any one of these modes might be excited in a given M dwarf. We assume that the probabilities of getting any of the configurations for a given P_m are comparable for the members of the pair.

To be definite, we ignore at least for the time being the non-oscillating modes shown by dots in Fig. 1. We stress that the oscillating nature of the nonaxisymmetric modes S1 and A1 is non-physical: there is a rotating frame in which each of these magnetic configuration is non-oscillating. In other words, oscillation of the modes S1 and A1 is just a result of longitudinal drift of the field patterns, viewed from a given line of sight.

The period of activity cycles for truly oscillating modes are

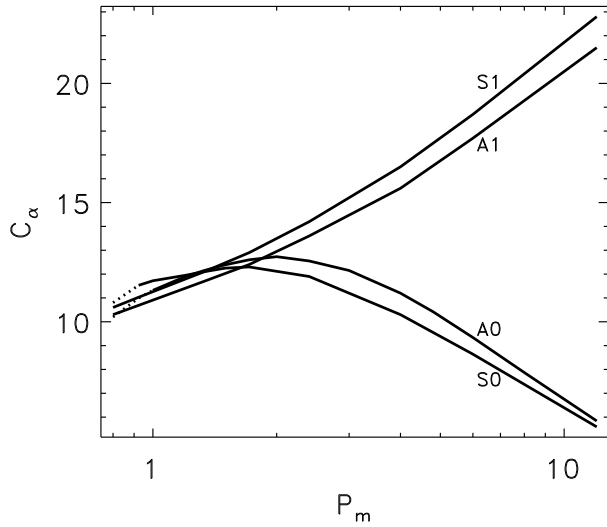


Figure 1. A dynamo model for a M dwarf: marginal values of C_α (Eqn. 2) for axisymmetric modes (A0) and non-axisymmetric $m = 1$ modes (A1) of dipolar symmetry, and axisymmetric modes (S0) and non-axisymmetric modes (S1) of quadrupolar symmetry. Dots indicate steady axisymmetric modes and the solid line shows the oscillatory modes.

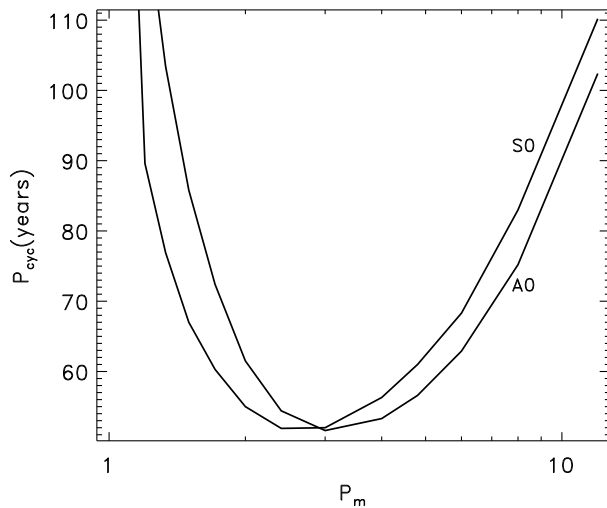


Figure 2. The period of activity cycles for truly oscillating modes (to be compared with the 22-year solar activity cycle).

shown in Fig. 2. Butterfly diagrams for these modes are shown in Fig. 3. Note that the activity waves propagate polewards.¹

As butterfly diagrams are irrelevant to nonaxisymmetric modes, we represent their field configurations by a diagram in latitude-longitude coordinates (Fig. 4)

Of course, such figures have previously been presented in the literature, but perhaps with not so much detailed inter-comparison. Our aim is to discuss to what extent the four dynamo modes under discussion can be distinguished observationally at present time or in the visible future and how it could in principle be done.

¹ Application of the same model to a sun-like star gave equatorward migration (see Fig. 5 in Kitchatinov et al. 2000).

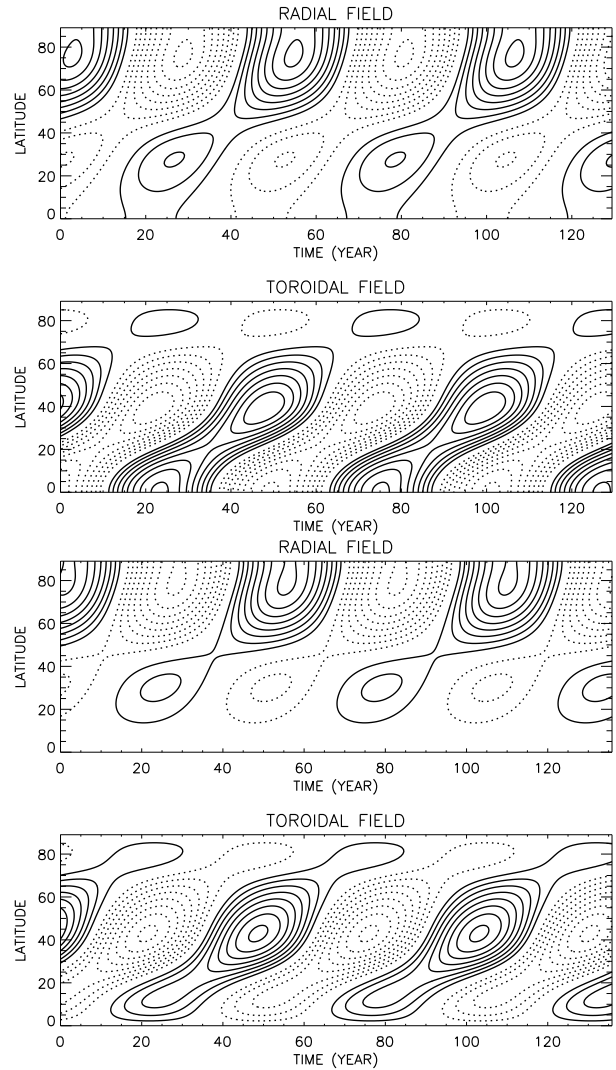


Figure 3. Butterfly diagrams for truly oscillating modes: upper pair - mode S0, lower pair - mode A0. Patterns of radial field at the surface and toroidal field at small depth are shown. $P_m = 2.4$.

4 DISTINGUISHING DYNAMO MODES OBSERVATIONALLY

First of all, no single mode from the above list has a configuration similar to the solar case, i.e. an oscillating axisymmetric mode of dipolar symmetry with equatorward propagation, and with toroidal magnetic field (i.e. stellar spots) located near to the stellar equator.

The following point looks instructive. The toroidal magnetic field becomes strong near to the stellar equator only for the mode S0. In other words, confirmed observation of stellar spots near the stellar equator is a diagnostic feature for the mode S0. Note however that, as can be seen from Fig. 3, more or less strong equatorial spots can also be observed for A0 configurations from some inclinations. The exact latitudinal pattern of toroidal field is likely to vary with the angular form of α , e.g. $\alpha \propto \sin^2 \theta \cos \theta$ would push it towards the equator (simply because the maximum of one of the dynamo drivers becomes closer to the stellar equator). In density-stratified convection, it seems likely that helicity (which is often used as a proxy of the α -effect) is indeed stronger near to the equator (Gastine et al. 2012). Excitation of mixed parity solutions is

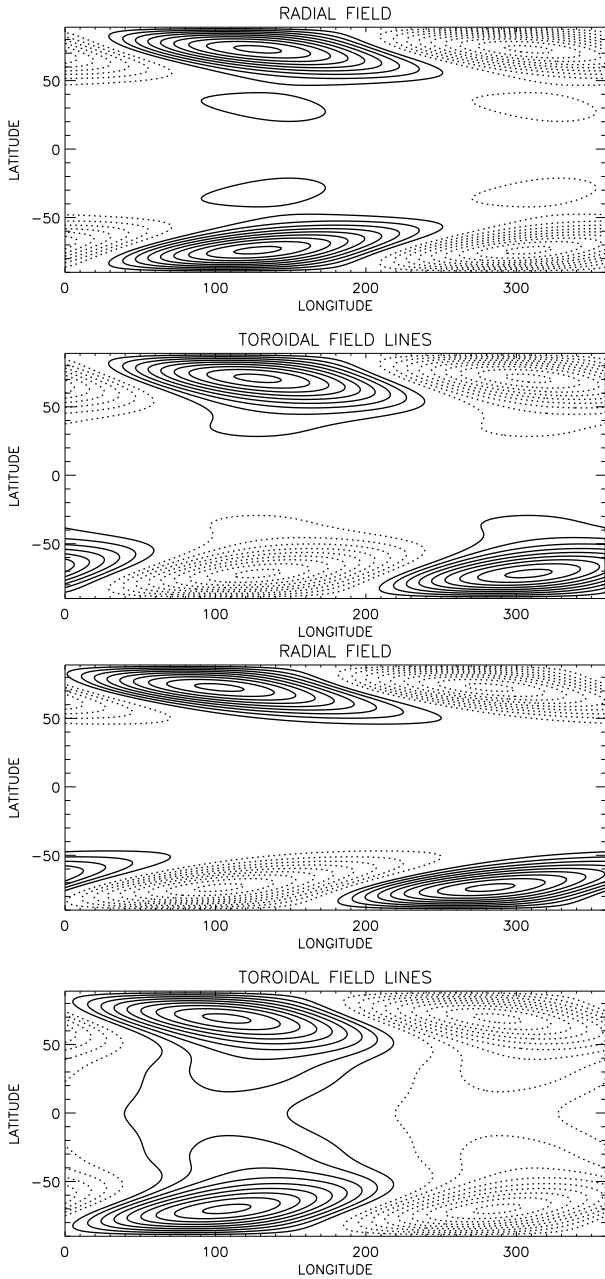


Figure 4. Configuration of nonaxisymmetric modes in latitude-longitude coordinates: upper pair – mode A1, lower pair - mode S1. $P_m = 1.3$.

known for nonlinear spherical dynamos (e.g. Brandenburg et al. 1989; Jennings & Weiss 1991) and for solar activity at the end of the Maunder minimum (Sokoloff & Nesme-Ribes 1994), and would also probably complicate interpretation.

Modes S1 and A1 have a pronounced longitudinal modulation of their nonaxisymmetric toroidal fields. We note that photometric data for the Ca lines obtained in the framework of the H-K project allow recognition of rotation modulation for some stars (Baliunas et al. 1995). Remarkably (Katsova et al. 2010), this modulation is well-pronounced not for the stars where the activity cycle is strong (“excellent” in the classification of Baliunas et al. (1995)), but rather for the stars where cycles are moderate (“good” of Baliunas et al.’s classification). If such modulation were to be

isolated for flare and flat stars in the classification of Baliunas et al. (1995), i.e. for stars without marked cycles, these stars could be considered to have magnetic fields of S1 or A1 configuration.

In order to distinguish between S and A modes it is necessary to compare the magnetic field direction in “Northern” and “Southern” hemispheres. The problem is that to perform this test observationally a sample of M dwarfs with rotation axis having large inclination angle with respect to the line-of-sight (ideally perpendicular) must be chosen and compared. Recent development of Zeeman-Doppler Imaging (ZDI) has provided us with magnetic maps of a number of stars. These maps can already be used to test at least some dynamo scenarios. For instance, Morin et al. (2008a), Morin et al. (2008b), Donati et al. (2008), and Morin et al. (2010) explored the surface magnetic field geometry and its evolution in a sample of M dwarfs consisting of partly and fully convective objects. Only circularly polarized Stokes V spectra were used in this analysis. Therefore, the magnetic maps presented in these studies reflect mostly the large-scale magnetic structures that do not cancel out in polarized light (if a sufficient number of observed time-series is available to cover the full rotation cycle of the star uniformly).

The main results of the ZDI studies are the existence of a switch in the magnetic field geometry between partly and fully convective M dwarfs: partly convective stars tend to host non-axisymmetric fields with dominant toroidal components, whereas axisymmetric dipole-like fields are found in fully convective stars. The distribution of field topologies, however, was found to be even more complicated. In particular, objects with weak toroidal fields were found among rapidly rotating fully convective stars. This pointed towards a possible dipolar breakdown so the stars with similar stellar parameters can host either dominant poloidal or toroidal configurations (see Fig. 15 in Morin et al. (2010)). A possible explanation for these observational findings was discussed in Gastine et al. (2013) who interpreted the magnetism of late M dwarfs as a result of a dynamo bistability and the choice of the final dynamo state in the models discussed above depends on initial conditions and does not change with time. We note here that, because our dynamo models are linear, they cannot provide evidence for bistability: the choice of the final dynamo state is fixed by the initial conditions. It is important to stress that no signature of a global magnetic topology change in individual stars has been seen. It may be that much longer monitoring is required to observe such changes (which, in fact, would be a crucial test for the bistability scenario). Note however that the activity cycles in M dwarfs are expected to be much longer than that of the Sun. Kitchatinov et al. (2014) suggested a model for the observed change of state that depends on the underlying activity cycle.

We note here some further points concerning the bistability problem. Gastine et al. (2013) (see also Schrunner et al. (2012)) reported dynamo bistability at low Rossby Ro number from a 3D model, i.e. the dynamo action either produces a strong stable dipolar field without any significant time variation (α^2 -dynamo), or a much weaker field which may possibly oscillate and be described by an $\alpha^2\Omega$ -dynamo. The choice of the final stable attractor depends on the initial conditions, or the prior physical conditions in the stars in their early stages after their formation. For slower rotators ($Ro > 0.1$), a dipolar breakdown is reported as strong dipole field become less likely when rotational influence on the convective flow becomes secondary. In principle, our illustrative model includes the possibility of a steady axisymmetric dynamo (dotted line in Fig. 1) and we recognize that further investigation may result in identification of this possibility with the actual field configurations in M dwarfs.

We can now try to compare our model predictions with the available ZDI maps. We first note that almost all stars with dominant non-axisymmetric toroidal components from the final sample of Morin et al. (2010) demonstrate similarities with the dipole-like, non-axisymmetric A1 mode (see Fig. 4). However, the observed orientation of the meridional component of the magnetic field does not agree with that predicted. For example, the radial field component of EV Lac is consistent with that of the A1 mode (see Morin et al. 2008b), but the B_ϕ component does not seem to show the expected surface distribution. If we ignore the B_ϕ component and concentrate only on B_r , then the signatures of mode A1 (which changes in sign along longitude) are found among both the groups of partly and fully convective stars, such as, say, GJ 1245 B, GJ 1156, DT Vir, GJ 182 and some others. Note that the A1 mode is only a plausible explanation of the observed picture of the magnetic field distribution in the framework of the dynamo modes that we consider in our study. Of course, this in no way proves that the actual magnetic field pattern in these stars can be described by such a simple model. Also note that our dynamo model may be not fully adequate especially at the stellar surface and that we show toroidal magnetic field distributions slightly below it. (Remember that our boundary condition is of zero toroidal field at the surface – see the short discussion in Sect. 2.)

On the other hand, the mode S1 never seems to be observed. Many objects demonstrate a distribution of radial field, which is characterized by opposite polarities in Northern and Southern hemispheres at all longitudes, while a change in polarity would be expected. Thus this disagrees with predictions for both A1 and S1 modes. Two stars, YZ CMi and DX Cnc, seem to show a possible transition between A1 and S1 modes during subsequent observing epochs, but this results is not well constrained by the ZDI maps, and also the distribution of B_ϕ does not agree with that of any of the predicted modes.

The detection of A0 and S0 modes is more difficult because the existing ZDI maps better represent the large-scale magnetic structures and not the small-scale structures that might be associated with stellar spots. However, we note that objects with detected non-axisymmetric toroidal configurations often show localized magnetic structures that could be characterized as spots. Stars such as DS Leo, DT Vir, GJ 182, GJ 1156, and GJ 1245 show spotty patterns of the distribution of B_r on their surfaces. These spotty structures evolve on time scales of years, and thus can be used to construct butterfly diagrams. Unfortunately, similarly to the cases discussed previously, the observed distribution of B_ϕ does not agree with those predicted. In some stars we see the appearance of single large scale spots and not a group of spots with different polarities distributed along a given latitude, while in others (e.g. DT Vir, DS Leo, and OT Ser) very complex surface structures are detected and these stars are certainly good candidates for future monitoring and the detection of A0/S0 modes. In this context it looks attractive to suppose that the spots at M dwarfs are caused by radial magnetic field rather by eruptions of subsurface toroidal magnetic field, as is the case on the Sun.

Another distinct feature of the observed magnetic field distributions is the presence of polar spots in the majority of fully convective objects. These spots can have positive (DS Leo, EQ Peg A) or negative (CE Boo, AD Leo, YZ CMi, WX UMa, GJ 51) signs of B_r . It is unlikely that we observe a group of spots because only a single polarity is detected. Therefore, these magnetic polar spots look simply like poles of the large-scale dipolar field. Note that these polar spots also change their shapes, as detected for e.g., YZ CMi. This possibly implies that also other stars with polar

spots should show the same evolution and their non-detection is connected with too short monitoring time.

It is interesting to note that the formation of polar spots has recently been modelled by Yadav et al. (2015) who found that, under certain conditions, their distributed dynamo models can spontaneously generate large-scale dark spots at high stellar latitudes. Thus, these models represent an alternative explanation of the observed magnetic field geometries in rapidly rotating low mass stars.

We may conclude at this point that the signatures of A0 and S0 modes, i.e. the presence of equatorial spots, can indeed be found in M dwarfs with strong toroidal fields, but it is hard to see stable patterns in their evolution. This is plausibly because the observations of these stars do not extend over long enough time intervals.

It follows from the above considerations that it is not possible to distinguish unambiguously between different dynamo modes from the available ZDI maps. The main limitation is the absence of long-time monitoring (i.e over several years). On the other hand, it is already possible to see a clear distinction between, say, A1 and S1 modes in some stars, at least from the analysis of the radial field component. Additional monitoring is strongly needed.

In order to put tighter constraints on the possible dynamo modes, observations of stars with large inclination angles ($60^\circ - 70^\circ$) are needed. Among stars from Morin et al. (2010), there are many that already meet this requirement, but none of them has an inclination larger than 70° . Nevertheless, the construction of the sample of stars with sufficiently large inclination angles does not seem to be problematic. The only difficulty is that inclination angles are often derived from ZDI itself so it is impossible to know these angles before actual phase-resolved observations. If rotational periods are known (say, from analysis of observed light curves) then inclinations can be derived from spectroscopically known $v \sin i$ values. In many cases, however, spectroscopic $v \sin i$ values are not accurately constrained which thus results in large errors in inclination. Interferometry is an alternative technique that may provide model independent estimates of inclination angles, but its abilities (in most cases) are not yet sufficient to resolve the surfaces of small and faint M stars.

Despite the detected changes in the magnetic field topology from Stokes V spectra, no strong evidence of the same changes have been noticed from the analysis of unpolarized light, as discussed in Shulyak et al. (2014). The authors explored the distribution of magnetic filling factors on surfaces of four M dwarf stars (from the very magnetically sensitive lines of the FeH molecule) and found similar distributions in all of them. Note that no information about the magnetic field orientation could be derived from this study. The only trend the authors could detect was in the distribution of filling factors and the strength of the surface magnetic field, which seem to depend on the rotation rate. However this is still inconclusive because of the small sample of stars used.

The only way to distinguish unambiguously between dynamo modes is by monitoring individual M dwarfs in polarized light by all possible means, in order to construct time-series of ZDI maps. By tracking the evolution of magnetic (and possible temperature) structures the corresponding butterfly diagrams could be constrained and comparison made directly with model predictions. Fig. 2 tells us that the monitoring should be quite long, over about 30 years (to be compared with the 11-year solar cycle); 15-year monitoring would be sufficient for preliminary conclusions.

Normally, ZDI techniques allow constraint of a few spherical harmonics of the surface magnetic field, with a typical maximum spherical harmonic degree of about 5-10. Thus, if the dipole has a typical oscillatory cycle of 60 years then it is very plausible that

higher degree modes can vary on shorter timescales. For instance, in geodynamo (α^2) models, the timescales of secular variations of the magnetic field obey a $1/\ell$ law (Christensen et al. 2012). High-quality observations and time-tracking over 5-10 years would then be sufficient to see a notable secular variation of the magnetic field in the higher spherical harmonic degrees. It looks thus promising in this respect to observe rapidly rotating stars such as, say, V374 Peg ($P = 0.44$ d, Donati et al. 2006; Morin et al. 2008a). Although no change in the magnetic field topology was reported between the two years of observations (2005 and 2006), continuing monitoring of this star is strongly recommended because the possible cycle is expected to be short.

On the other hand, a significant amount of information concerning magnetic configurations can be obtained using DI only, cf. that the solar magnetic cycle was isolated by Schwabe in the XIXth century before Zeeman splitting in sunspots was observed. DI techniques have existed for about 30 years but the time resolution of the published maps of M dwarfs at best only span several years. Note that the length of activity cycles is expected to scale with rotation rate. This issue was seems to have been first discussed by Noyes et al. (1984). The tendency is to some extent confirmed by observations in the Wilson program (Saar & Brandenburg 1999). Observing the most rapidly rotating stars may be a relatively easy task. For instance, the rapidly rotating YZ CMi, DX Cnc, GJ 1156, GJ 51, etc. are potentially good targets with which to begin. In addition, the strength of the surface magnetic field clearly correlates with the rotation rate: it grows steadily with decrease of rotation period until a saturation limit is reached (Reiners et al. 2009). Importantly, as was shown in Pizzolato et al. (2003) and more recently in Reiners et al. (2014), the magnetic field strength in the non-saturated regime is a function only of rotation rate and does not depend on any other stellar parameters (such as mass or radius), while the saturation limit depends on the bolometric luminosity and thus differs from star to star. Therefore, studying rapid rotators could produce interesting constraints on dynamo action in M stars.

So far all ZDI maps have been obtained by using observations in Stokes V only. In order to resolve more surface detail, mapping of both linear and circular polarization is needed. This imposes very strong observational constraints because, e.g., long integration times would be needed to collect sufficient signal in linearly polarized light. High spectral resolution is also an essential requirement. The instruments available for M dwarf research are ESPaDOnS@CFHT (3.6 m, $R = 65\,000$, 370–1005 nm), NARVAL@TBL (2 m, $R = 65\,000$, 370–1005 nm) (Donati et al. 1997), HARPSpol@ESO (3.6 m, $R \approx 110\,000$, 378–691 nm) (Snik et al. 2011; Piskunov et al. 2011), and HiVIS@AEOS (3.7 m, $R \approx 50\,000$, 500–1000 nm; $R \approx 33\,000$, 1000–2500 nm) (Thornton et al. 2003; Harrington et al. 2006; Harrington & Kuhn 2008), as well as future instruments such as PEPSI@LBT (2×8.4 m, $R = 120\,000$, 383–907 nm) (Ilyin et al. 2011), SPIRou@CFHT (3.6 m, $R \approx 70\,000$, 980–2350 nm) (Artigau et al. 2011), and CRIRES@VLT (8 m, $R = 100\,000$, 1000–5300 nm) (Kaeufl et al. 2004). Observing at infrared wavelengths with high spectral resolution is superior to visual observations because of the cool temperatures of M dwarfs, and that the scaling of Zeeman splitting is proportional to λ^2 . Thus instruments operating in the near-infrared would contribute greatly to studying the evolution of magnetic topologies in M dwarfs.

5 DISCUSSION AND CONCLUSIONS

Based on a relatively simple and standard mean field dynamo model for M dwarfs we have presented four dynamo generated magnetic configurations which can be excited in the framework of the model. In this model, the parameter which determines the excited dynamo mode is the magnetic Prandtl number P_m . Note that we identify the excited mode with the mode with the lowest marginal dynamo number. We appreciate that for more supercritical non-linear models this simple idea may become inadequate. However, we intend to begin our analysis with simple models and improve them if observations will so require.

We started from the conventional expectation that observations and dynamo theory are still quite remote from each other, and comparison is a very uncertain and problematic undertaking. After making the comparison it appears plausible that the situation may not be quite as difficult as expected and some preliminary identifications may be obtained immediately. We see that at least some of the configurations look closer to observations than others. In particular, signatures of the S1 configuration appear never to have been observed, while prospects for identification of the A1 configuration perhaps look more promising. The surface distribution of radial magnetic field looks rather similar to the predictions of dynamo theory while the distribution of toroidal components in dynamo models appears quite different to the observational data.

Note that systematic investigation of magnetic activity of M dwarfs can be useful for the understanding of stellar hydrodynamics. Indeed, Eq. (2) suggests that dynamo action becomes stronger for stars with larger stellar radius, if other governing parameters are unchanged. In practice however turbulent diffusivity increases with stellar radius so the stellar hydrodynamical model predicts that dynamo action becomes weaker for more massive stars. On the other hand, Fig. 1 tells us that preferred magnetic fields configurations are specific for weaker and stronger dynamo action, as given by the C_α parameter. Confronting these expectations with future observations we may hope to deduce the actual scaling of turbulent diffusivity with stellar radius.

In principle, we could start fitting dynamo models in order to reproduce an improved phenomenology for B_ϕ . However our feeling is that, taken overall, the results on the topic are still not stable enough, and it would be better to discuss the available and forthcoming results in the framework of the strategy suggested here, as well as bearing in mind the possibilities discussed above when analyzing any forthcoming and improved dynamo modelling. In any case, it looks plausible that the joint effort of observers and dynamo modellers will be able to clarify the problem in the foreseeable future.

We recall the brief overview of dynamo modelling given in Sect. 1, and appreciate that the dynamo model we have used can of course be criticized on a number of grounds. However it seems remarkable that all dynamo driven magnetic field configurations for M dwarfs obtained in its framework give a magnetic field that is concentrated at quite high latitudes, i.e. they predict magnetic stellar activity in regions that are far from the stellar equator. Based on solar experiences, this result is quite unexpected and deviates substantially from expectations. On the other hand, the formation of high-latitude spots in rapidly rotating fully-convective stars is also predicted by self-consistent global dynamo models presented by Yadav et al. (2015). This may indicate that the dynamo mechanism in cool rapidly rotating stars is quite different from the solar case.

We finally stress again that our intention has been to explore a possible methodology for investigation of the phenomenology of M

dwarf magnetism. We have illustrated this by reference to a particular dynamo model, but as more sophisticated and definitive models for the magnetic fields are developed, the principles will remain relevant.

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